Rafter stiffeners – needed or not?

Zealous application of the rules in EN 1993-1-8 has resulted in stiffeners being provided in rafters at the "sharp end" of portal frame haunches – where the haunch flange meets the rafter. David Brown and Bogdan Balan of the SCI report on the investigation to demonstrate that in the particular arrangement of portal frame haunches, the rules in BS 5950 are a more appropriate assessment of the need (or not) to add reinforcement.

The problem at the "sharp end"

The "sharp end" of the haunch is the point where the haunch flange meets the underside of the rafter flange, as shown in Figure 1. In UK practice, the haunch flange is connected to the underside of the rafter with a weld across the rafter flange, often with a leg length equal to the thickness of the haunch flange.

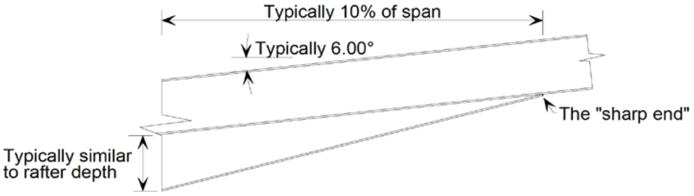

Figure 1: Typical haunch details

The concern at the "sharp end" is whether stiffeners are required in the rafter. In some cases, it is absolutely clear that stiffeners must be provided. If there is a plastic hinge at that location, and the transverse force exceeds 10% of the shear resistance of the cross section, web stiffeners must be provided in the rafter within $h/2$ of the hinge location. This is covered by clause 5.6(2) of BS EN 1993-1-1. BS 5950 has equivalent requirements in clause 5.2.3.7. The recommendations in this article do not change these requirements for stiffeners at plastic hinge locations. When the detail is as shown in Figure 1, the calculation of the transverse force applied to the rafter may be uncertain, but this will be covered later in this article.

Connections to unstiffened flanges

The Eurocode requirement leading to the provision of stiffeners in the rafter is clause 4.10 of BS EN 1993-1-8, which covers welded connections to unstiffened flanges. The situation is shown in Figure 2, with an indicative non-uniform stress distribution. The non-uniform stress distribution is due to the area adjacent to the web being relatively stiff, compared to the more flexible flange tips. Design codes deal with this by determining an effective width over which the stress may be assumed to be uniform.

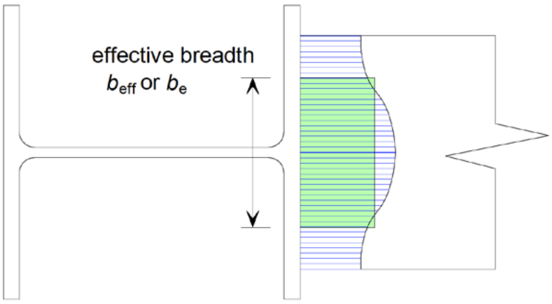

Figure 2: Welded connection to unstiffened flange

The effective breadth is calculated by assuming the web and root radius (or weld) is stiff and allowing for some distribution through the flange, as shown in Figure 3. Distributions range from 1 in 3.5 (BS EN 1993-1-8) to 1 in 2.5 (clause 6.7.5 of BS 5950).

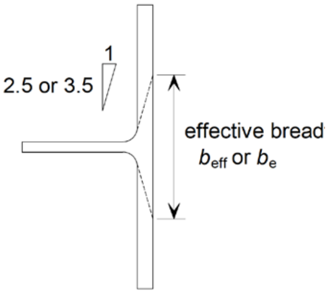

Figure 3: Calculation of effective breadth

The effective breadth is always narrower than the width of the flange. Clause 4.10(3) of BS EN 1993-1-8 requires that:

$b_{eff} \geq (f_{y,p}/f_{u,p})\, b_p$ where the subscript "p" refers to the plate. If this requirement is not satisfied, the clause notes "Otherwise the joint should be stiffened".

If the plate (in this case the haunch flange) was in S355, then

$b_{eff} \geq (355/470)\, b_p$ or $b_{eff} \geq 0.75 b_p$

Since the haunch flange is usually as wide as the rafter this requirement is generally not satisfied and the result is that stiffeners are required. Some design software report this as an advisory note rather than a "fail".

It should be noted that the Eurocode requirements are not influenced by the load which is being transferred – even if the load were trivial, stiffeners may be required because the requirement is only based on the geometry of the joint.

Bring on the FE analysis

With support provided by BCSA, SCI proceeded to prepare a series of FE models, analysing typical haunch geometries and various levels of load. Mesh sizes were carefully considered, elements in the model carefully selected and the results validated by calculating the resulting shears forces and bending moments computed from the stress of individual elements in the cross-sections considered at various positions along the model. Full details of the FE work are available from the SCI.

The models included an unwelded length of the haunch web (where physical access makes welding impossible) and truncated haunches, both as shown in Figure 4. Models were analysed with and without stiffeners in the flanges, and with different haunch flange thicknesses. The geometry of the haunch and rafter was arranged to reflect typical roof slopes and typical haunch dimensions found in portal frames. This qualification is important, as the design recommendations are for orthodox portal geometry, where the angle between the haunch flange and the rafter flange is generally around 7 - 12°. The design recommendations which follow should not be applied out of context.

Separately, transverse loads of increasing magnitude were applied to a plain rafter section, so that the resulting stress patterns could be examined and compared to the codified requirements to provide web stiffeners under concentrated loads.

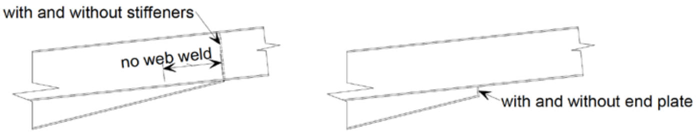

Figure 4: Haunch arrangements investigated

▸26

▸24

A typical equivalent stress plot is shown in Figure 5. Several more stress plots could be shown, but the results are not significantly different. After carefully reviewing several models it was concluded that there were no indications that the rafter required stiffening.

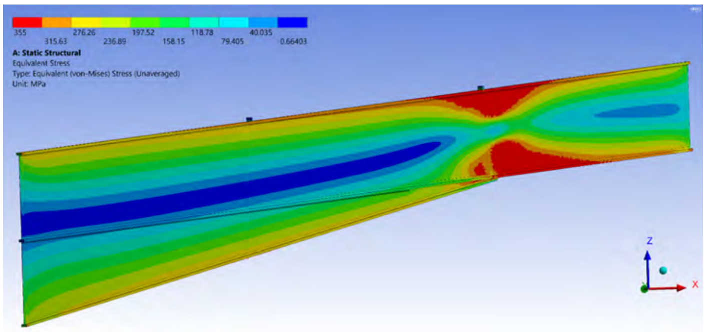

Figure 5: Typical equivalent stress plot

Calculation of the transverse force

Assuming the haunch flange is welded to the underside of the rafter, the transverse force can be calculated as the component of the force in the haunch flange perpendicular to the axis of the rafter. The force in the haunch flange can be determined by calculating the properties of the compound section immediately adjacent to the "sharp end" of the haunch and calculating the stress in the haunch flange. It was found that this approach (perhaps unsurprisingly) gave a good correspondence with the force derived from the FE models.

If the design bending moment is relatively high at the "sharp end" some local plasticity and strain hardening is to be expected – so designers following the recommended approach may find that the calculated force in the haunch flange equates to the cross sectional resistance of the haunch flange. This has implications for the weld between the haunch tip and the rafter, as discussed later.

Recommended design rules

Although the FE analysis did not identify reasons to reinforce the rafter, to have no design rule at all might be considered reckless. The recommended approach is therefore to follow the guidance given in BS 5950, which is supported by several decades of successful practice. Although BS 5950 has similar design rules for welded connections to unstiffened flanges as the Eurocode, the critical difference is that the BS 5950 guidance relates the need for stiffening to the applied force, rather than being based on joint geometry alone.

The BS 5950 procedure is to calculate the maximum force which can be carried over the effective width. The requirement for stiffening is given by (in BS 5950 nomenclature):

If $b_e < 0.5(F_x/P_x)\, b_p$ then stiffeners are required, where:

F_x is the applied force (the component of the force in the haunch flange)

P_x is the resistance (the maximum force which can be carried over the effective breadth)

Calculation example

In this example, both the rafter and haunch are assumed to be a 457 × 191 × 67 UB in S355.

In the haunched region, immediately adjacent to the "sharp end", the cross section and calculated properties are shown in Figure 6.

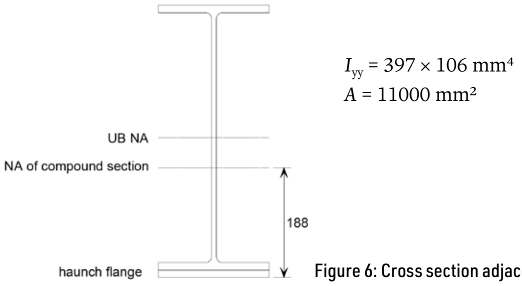

Figure 6: Cross section adjacent to the "sharp end"

Assuming an applied moment at this location of 480 kNm, the average stress in the haunch flange is 219 N/mm². The force in the haunch flange is 533 kN. If the included angle between the haunch flange and the underside of the rafter is taken as 8°, the force applied transverse to the rafter is 74 kN.

The limiting force P_x is given as:

$P_x = [4\sqrt{2}T_c^2 + (t_c + 1.6r_c)t_p]p_{yc}$ but $P_x \leq (5Tc + t_c + 1.6r_c)t_p p_{yp}$

where:

p_{yc} and p_{yp} are the design strengths of the column and plate respectively (in this case, of the rafter and haunch)

r_c is the root radius of the rafter

T_c is the flange thickness of the rafter

t_c is the web thickness of the rafter

t_p is the thickness of the connected flange (of the haunch)

The dimension t_p is measured parallel to the rafter. It is assumed that this dimension is equal to the weld leg length, which is equal to the thickness of the rafter haunch.

Therefore:

$P_x = [4\sqrt{2} \times 12.7^2 + (8.5 + 1.6 \times 10.2) \times 12.7] \times 355 \times 10^{-3} = 436$ kN

but $P_x \leq (5 \times 12.7 + 8.5 + 1.6 \times 10.2) \times 12.7 \times 355 \times 10^{-3} = 398$ kN

Then:

$$b_e = \frac{P_x}{t_p p_{yp}} = \frac{398 \times 103}{12.7 \times 355} = 88 \text{ mm}$$

According to BS 5950, stiffeners are required if b_e is less than:

$$0.5 = \left(\frac{F_x}{P_x}\right) b_p = 0.5\left(\frac{74}{398}\right) \times 189.9 = 18 \text{ mm}$$

Thus, according to BS 5950, since 88 > 18, no stiffeners are required – by a considerable margin.

If the BS EN 1993-1-8 rules are applied, $b_{eff} = 118$ mm. The limiting value of $0.75b_p$ is $0.75 \times 189.9 = 142$ mm, meaning that stiffeners would be required.

Truncated details

The truncated haunch detail shown in Figure 4 is not popular in the UK, but used in other parts of the world. The advantage of the truncated details is that the web is continuously welded and there is no large weld between the haunch flange and the rafter. If this detail is adopted, it is recommended that some form of welded end plate is provided at the end of the haunch. Without restraint the analysis confirmed that as expected, the tip of the haunch showed signs of distortional buckling.

Welds

Within the FE analysis, welds were modelled with a fine mesh and the same material properties as the parent metal. Full size (leg length equal to the haunch flange thickness) and smaller weld sizes were investigated. In all cases, at higher applied moments, equivalent stresses in the weld were approaching yield with some local plasticity. Physical strains were calculated at different locations in the weld. Whilst all strains were smaller than those measured when welds fracture, the strains with smaller welds were significantly larger than that of the full size weld. The recommendation from this comparison is that if the end of the haunch is to be welded, it should have a full size weld. A smaller weld may experience unacceptable deformations, based on the modelling exercise undertaken.

Conclusions

The work described in this article has demonstrated that in the very specific situation of orthodox portal frame construction (notably a small included angle between the haunch flange and the rafter), the requirement for stiffeners at the "sharp end" of the haunch can be based on the rules in BS 5950. This recommendation should not be applied in other situations. Stiffeners may still be required if there is a plastic hinge at the "sharp end" of the haunch. ■